LCA Case Studies

Ecology Profile of the German High-speed Rail Passenger Transport System, ICE

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Abstract

Intention, Goal, Scope, Background, Objectives. Environmental effects caused by the railway transport services have rarely been investigated in depth from a systemic point of view. A screening LCA, called ecology profile, of the German high-speed passenger train system, the ICE, is presented here, based on a study conducted by the University of Halle and the Deutsche Bahn AG, the major German rail operator. In this study, the resource consumption caused by traction, manufacturing and maintenance of ICE trains, as well as construction and operation of the supporting rail infrastructure and buildings, have been evaluated using cumulative energy demand (CED), cumulative material input per service unit (MIPS) and CO_2 emissions as indicators.

Methods. Approximately 200 items of inventory data were collected from DB AG experts, manufacturers, site balances and the associated literature. They were allocated in order to derive 100-person-kilometre-related mass and energy consumption figures. The appropriate CED, MIPS and CO_2 factors were applied in order to quantify the indirect efforts associated with the inventory data.

Conclusions. For the reference high-speed route investigated, Hanover-Wuerzburg, the railroad infrastructure does not contribute the high share of resource consumption to the life cycle of the transport service which was expected from other studies. For the reference route, the CED of the infrastructure contributes 13% to the total CED per 100 person kilometres, whilst the energy demand of the traction process dominates the life cycle. Within the railway infrastructure, the construction of tunnels and the heating of rail points during winter time are significant primary-energy active components, whereas the energy requirement for maintaining the railway stations is a minor factor in comparison. The environmental impact of new technologies for designing rail tracks have also been analysed. The new ballastless slab track technology investigated needs higher absolute resource inputs in the construction phase compared with the traditional gravel bed, but due to higher life expectancy, it competes favourably at the 100-person-kilometre level, at least in terms of material requirements. Efforts to reduce the traction energy consumption of the ICE train will have the greatest impact on the CED of the transport system. In summary, a total of 48 kg of solid primary resources are needed for a passenger to travel 100 km by ICE.

Recommendations/Outlook. The results presented can be used for modelling other high-speed railway transport systems. A comparison of the ecology profiles of the German, French and Japanese high-speed train systems would be of interest in order to identify potential areas for improvement. Additional studies are needed to evaluate the short-hop, commuter train service. Further efforts should be directed to comparing the infrastructure of the high speed train and that of highway road traffic.

Keywords: CED; CO_2 emission; cumulative energy demand; high speed transport; LCA; life cycle assessment; material input per service unit; MIPS; railway infrastructure; railway passenger transport

Introduction

Transport services are an integral part of the life cycles of almost all products and services. The railway system is regarded by the general public as one of the resource-efficient answers to our ever-growing demand for transport services. However, the quantitative data available on the ecological impact of the rail transport system is sketchy at best and limited to the traction process in most investigations on this subject. Apart from the traction energy required for actually moving the train, certain rail infrastructure components (tracks, railway stations, tunnels, bridges, etc.) can be assumed to be resource intensive as well. Until now, the environmental impact resulting from the construction, use and disposal phases of the rail infrastructure has rarely been investigated quantitatively and in depth. Initial studies on this aspect estimate the share of the infrastructure on the primary energy demand of the whole life cycle to be more than 50% [1].

A study, called *ecology profile*, was therefore initiated by the Martin-Luther University Halle-Wittenberg in close collaboration with the major German rail operator, the Deutsche Bahn AG (DB AG), to investigate the environmental effects of the rail transport system in depth, but with a restricted set of key indicators calculated from the collected data. The 'flagship' of the long distance passenger rail transport in Germany, the Inter City Express (ICE), was chosen as the subject of the study. The high-speed rail route between Hannover and Wuerzburg was selected as the reference route for infrastructure data collection. Thereupon, the special characteristics of the high-speed traffic such as increased energy consumption and high rail track quality demands were taken into account. An average ICE passenger travelling 325 km per journey[1] has been considered. The additional energy requirements for the passenger to travel from his/her starting location to the nearest ICE railway station and from the disembarking railway

[1] Calculated from ICE person kilometres in Germany per year and from number of ICE-passengers per year for 1999.

station to his/her final destination have also been considered in order to close the transport chain. While other infrastructure-oriented life cycle studies often use top-down data collection approaches (e.g. breaking down national values), bottom-up data was preferred whenever available in the ecology profile. Special importance was attached to a thorough investigation of the rail-track and railway station infrastructure.

1 Scope: What has been investigated?

The Inter City Express (ICE) is the backbone of the German long-distance rail transport system. It is a high-speed train that runs at speeds of up to 300 km/h, provided that the track is suitable for this speed. In the future, the long distance passenger transport service by rail will rely even more on the ICE in order to successfully compete with the internal German air transport system and road transport by car.

Until the introduction of the ICE 3 in 2000 and the ICE-T in 1999, two versions of the ICE were technically in service, ICE 1 and ICE 2. **Table 1** provides characteristic data for these two trains. In the present study, a mix of 40% ICE1 and 60% ICE2 trains has been evaluated. This mix is subsequently referred to as 'ICE' for short.

The life cycle of *immaterial services* (such as transports) comprises the life cycles of the direct or end materials, and end energies required to provide this service. To structure the data collection, the life-cycle of the ICE transport system was subdivided into so-called *main process elements (MPE)*, which are depicted in **Fig. 1** and discussed in the following chapter on inventory data. The MPEs are the first level of disaggregation based on transport functionalities (providing reliable tracks, catering for passengers, providing maintenance for the train, cleaning and servicing the train, etc). These main process elements are transport-system invariant; i.e. functionally equivalent process elements can be identified within the air and road transport systems. The MPEs of the ICE have been further subdivided into so-called *process modules.* These modules can differ significantly between the different traffic systems, e.g. the railway catenary system with the associated transformer is quite different from the petrol station in the car transport system.

For each MPE, a specific *reference unit* or functional unit is defined to provide a reference for the material and energy inventory data. For rail tracks, for example, the reference unit is the two-way rail track kilometre and year (rtkm·a).

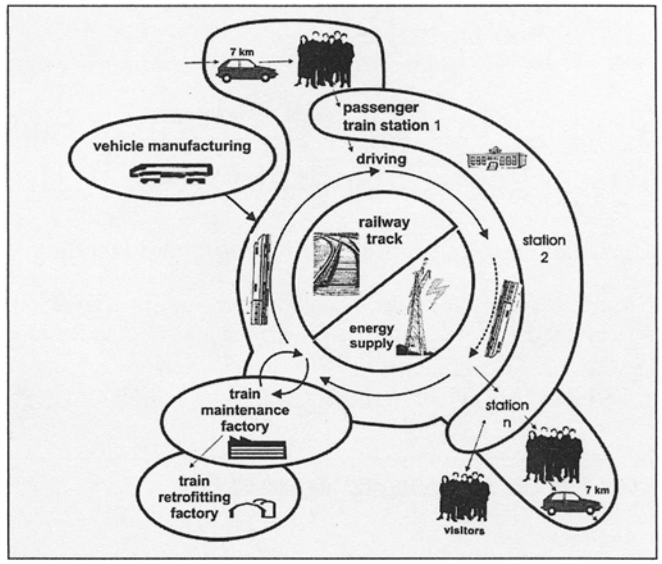

Fig. 1: Main process elements (MPEs) of the ICE transport

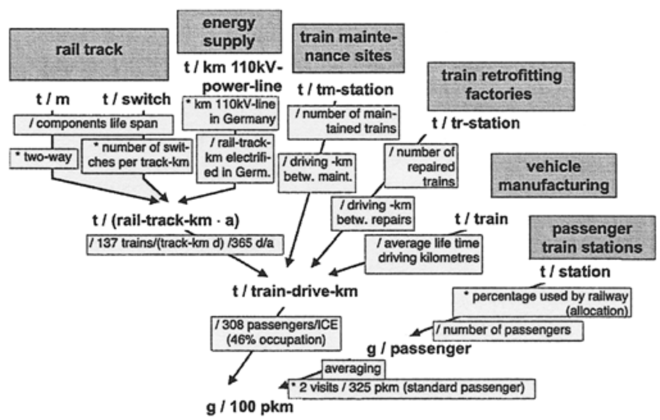

Fig. 2: Models for translating the different reference units of the MPEs to the functional unit, 100 pkm

This data per MPE-specific reference unit is then allocated to the *functional unit* of the whole-lifecycle of the transport system further on, i.e. to 100 person kilometres (*100 pkm*) as explained in **Fig. 2** and in the following chapter[2].

[2] Neither further splitting the modules nor extension of the product system were feasible, so an allocation based on physical relationships (e.g. train kilometres or gross ton kilometres) should be applied as required by ISO 14041.

Table 1: Characteristics of the German high-speed trains, ICE1 and ICE2

	ICE 1	ICE 2 (half train)
Special features	First generation, 2 traction heads, not separable	Half-train concept: two train sets can be coupled
Typical configuration	2 traction heads + 12 wagons (1 restaurant)	1 traction head + 1 control head (cab car) +6 wagons (1 service wagon)
Length	358 m	200 m
Traction energy	9600 kW	4800 kW
Max. speed	280 km/h	280 km/h
Seats	approx. 669	approx. 391
Weight	782 t	410 t
In operation since	1991	1996
Number of trains in service	59	44 train sets

The *Hannover-Wuerzburg reference route* is a high-speed track designed for a maximum speed of 250 km/h. It was built between 1973 and 1991. The 325 km of two-way track pass through mountainous terrain. It includes 120 km of tunnels (38 km-%), 26 km of rail bridges (8 km-%) and about 1 km-% of railway or roadway bridges.

The impact assessment of the ICE ecology profile study was restricted to a small set of indicators mainly relating to primary energy and raw material consumption and to the global warming potential associated with CO_2 production. Other environmental effects directly related to transport systems, such as landscape use, habitat segregation, noise emissions, have not been included in the present study because the corresponding quantitative models are less well-founded in LCA.

The *cumulative energy demand (CED)*, as defined in [2], relates the end material and end energy consumption to the primary energy drawn from nature at any stage of its life cycle, thereby taking into account what is called 'grey energy' in some studies. For instance, the end energy electricity requires refinement processes with larger associated conversion losses than the end energy petrol. Therefore, the CED factor for German grid electricity is 3.0 (primary energy per end energy requirement) versus 1.3 for petrol. Comparison of energy intensities of different systems should be based on primary energy.

CED factors are not natural constants but depend, for example, on the technology employed. Consequently, the values quoted in the literature differ. Mainly GEMIS 4.0 CED factors have been used in the present study (**Table 2**). This data is available for the materials and end energy forms of interest in this study; they have been collected for circumstances predominant in western Europe [3]. By convention, the unit of kilowatt hours (kWh) for all end energy forms and the joule (MJ or kJ) for all primary energies are used in the following chapters.

While the CED is an indicator for the primary energy consumed during the life cycle in question, the *MIPS indicator* (material input per service unit), as defined by the Wuppertal Institute [4], aggregates the masses of all primary materials 'touched', including excavated material, overburden, cooling water and combustion air.

In terms of the depletion of limited primary resources and the associated influence on the landscape, the abiotic solid raw materials consumed are of greatest concern. Consequently, the present study concentrated on the indicator, 'MIPS without water and air'. MIPS as a whole is sometimes criticised within the LCA community for aggregating different kinds of materials without regarding their specific ecological impact or importance [10]. But in order to get a holistic notion of the material intensity of the at first sight, seemingly immaterial, transport service, this indicator appears adequate.

Some end materials used for the construction of the railway infrastructure, such as rails and track gravel, catenary system cables, etc., can be *recycled* as components, materials or secondary raw materials. However, due to the high mechanical demands of high speed train traffic, virgin materials are usually preferred, e.g. for the construction of track gravel beds. Basically therefore, no account has been taken of the specific recycling efforts of the railway industry in the present study. All end materials consumed were allocated to the ICE infrastructure, the first production system in the recycling chain[3]. In this way, recycling was considered as a technology average as integrated into the CED and MIPS factors.

CO_2 emissions associated with the end materials and energies have also been calculated according to the values recommended by GEMIS 4.0 [3].

2 Inventory: End Energy and Material Consumption

Inventory analysis covers the *end (or direct) material and energy consumption*, i.e. those materials and energies consumed by the processes which are under management control of railway companies, e.g. the DB AG. Some relevant data of the approximately 200 inventory values collected is presented in **Table 3**, arranged according to their respective MPEs. As much of the data was supplied by railway experts or internal documents of the DB AG, data quality can be regarded as comparatively high on average. In Fig. 1, the MPEs are given within the transport chain of the ICE.

An obvious environmental impact is caused by the consumption of *energy during the train journey*. This MPE includes the actual traction energy, but also the so-called board energy needed for air conditioning, lighting the train and operating the train restaurant. A certain quantity of so-called passenger overhead energy consumed, when the passenger is travelling between the train stations and the starting or final destination by car, is assumed (2 x 7 km x 1.6 passengers/car) to address the home-to-home characteristics of the passenger transport service. Furthermore, a quantity of overhead energy was attributed to train trips to and from maintenance works, repair works and night-time parking stations. The reference unit of this MPE is the train kilometre. Allocation from the train kilometre level to the person kilometre level is done by dividing by the average occupancy of the ICE train as provided by DB AG statistics (309 passengers = 46% of ICE seats).

The rail driveway part of the MPE *railway track* consists of the track bedding and the associated substructure. Apart from the rails (made of steel), railroad sleepers (made of concrete reinforced with steel) and the standard gravel for bedding have to be considered. The substructure basically consists of bulldozed and compressed soil or sand.

There is an alternative technology under development for building rail tracks, so-called *ballastless slab tracks* in which the rail and sleeper system is connected with a firm bedding made of concrete or some other binding material like asphalt. The new high speed railway route between Cologne and Frankfurt, currently under construction, is completely being made up of ballastless slab tracks.

[3] An alternative model, in which material production efforts were distributed among different recycling stages by using an index value calculated by amount × quality (assuming exponentially decreasing qualities in each cycle), led to a 21% decrease of the life cycle CED of the railway track infrastructure on a kilometre and year basis.

Table 2: CED, MIPS and CO_2 characterisation factors used in this study

	KEA		Ref.	Note	CO_2		Ref.	Note	MIPS w/o water and air		Note data based on [4]	Density [t/m³]
Aluminum	143	MJ/kg	[3]	:=70% prim. 30% sec. Germany	8996	g/kg	[3]	:=70% prim. 30% sec. Germany	67.8	t/t	:=70% prim. 30% sec. Germany	
Aluminum primary	193	MJ/kg	[3]		12171	g/kg	[3]					
Aluminum secondary	27.3	MJ/kg	[3]		1590	g/kg	[3]					
Basalt	0.24	MJ/kg	[6]	diabas w/o transport	17	g/kg	[6]	diabas w/o transport	1.47	t/t	broken	
Bricks	2.02	MJ/kg	[3]		192	g/kg	[3]	building brick	2.16	t/t	porous building brick	
Ceramic	4.30	MJ/kg	[8]	:=clay tiles	282	g/kg	[6]	:=clay tiles		t/t		
Concrete	1.00	MJ/kg	[3]	concrete B25. w/ reinforc.steel. 10% water	172	g/kg	[3]	concrete B25. w/ reinforc.steel. 10% water	1.39	t/t	w/ reinforc.steel; concr. B25. 10% water	1.95
Copper	46.7	MJ/kg	[3]		3772	g/kg	[3]		251	t/t	50% prim. 50% sec.	
Copper. primary	–	MJ/kg			–	g/kg			502	t/t		
Copper. secondary	–	MJ/kg			–	g/kg			10.4	t/t		
Diesel fuel	43.0	MJ/kg	[5]		3616	g/kg	[3]	diesel Germany; manuf.+combustion	4.60	t/t	incl. combustion air	0.832
Drinking water	–	MJ/kg	assum.		0	g/kg	assum.		0	t/t	assum.	
Elect. gas comb.	7.42	MJ/kWh	[3]	gas-GUD. w/o distr.	402	g/kWh	[3]	gas-GUD. w/o distr.				
Elect. lignite comb.	9.20	MJ/kWh	[3]	3 plants. w/o distr.	1022	g/kWh	[3]	3 plants. w/o distr.				
Elect. nuclear plant	11.4	MJ/kWh	[3]	w/o distr.	32	g/kWh	[3]	w/o distr.				
Elect. oil comb.	12.8	MJ/kWh	[6]	w/o distr.	1005	g/kWh	[6]	w/o distr.				
Elect. pit coal comb.	9.51	MJ/kWh	[3]	3 plants. w/o distr.	900	g/kWh	[3]	3 plants. w/o distr.				
Elect. water pant	3.82	MJ/kWh	[3]	large plant.w/o distr.	39	g/kWh	[3]	large plant.w/o distr.				
Elect. wind plant	3.73	MJ/kWh	[3]	Mid-range park. w/o distr.	19	g/kWh	[3]	mid-range park.w/o distr.				
Electricity	10.7	MJ/kWh	[3]	:= grid electricity for Germany	647	g/kWh	[3]	:= grid electricity for germany	2.00	MJ/kWh	OECD mix	
Glass	14.3	MJ/kg	[6]	flat glass	1155	g/kg	[6]	flat glass	3.82	t/t	flat glass	
Gravel	0.24	MJ/kg	[6]	:= basalt	17	g/kg	[6]	:= basalt	1.47	t/t	:= basalt	1.5
Grid electricity	10.7	MJ/kWh	[3]	German local mix. w/ distr	647	g/kWh	[3]	german local mix.w/ distr	2.00	MJ/kWh		
Grit	0.04	MJ/kg	[3]	quarry stone	3	g/kg	[3]	quarrystone		t/t		1.8
Insulation material	12.7	MJ/kg	[3]	:=mineral wool	976	g/kg	[3]	:=mineral wool	5.69	t/t	mineral wool	
Iron	13.0	MJ/kg	[3]	cast iron	926	g/kg	[3]	Cast iron	6.58	t/t	raw iron	
Mineral wool	12.7	MJ/kg	[3]		976	g/kg	[3]		5.69	t/t		
Natural gas	4.93	MJ/kWh	[3]		267	g/kWh	[3]		4.86	MJ/kWh	incl. combustion air	
Non-iron metals	95.0	MJ/kg	[3]	:=50% Cu+50%Al	6384	g/kg	[3]	:=50% Cu+50%Al	160	t/t	:=50% Cu+50%Al	
Petrol	43.5	MJ/kg	[5]		1813	g/kg	[3]	petrol leadfree Germany; manuf.+combustion	5.83	t/t	from pyrolysis	0.726
Plastics	35.2	MJ/kg	[6]	:=40% PVC+40% PE+20%Styrol	2270	g/kg	[3]	:=50%PVC+50%PE	8.71	t/t	:= PVC	
Plastics. PE		MJ/kg			2187	g/kg	[3]	HDPE-pipe 99		t/t		
Plastics. PVC	39.9	MJ/kg	[8]		2352	g/kg	[3]	PVC-pipe 99	8.71	t/t		
Rail electricity	10.3	MJ/kWh	[3]	mix DB AG; see **Table 6**	596	g/kWh	[3]	mix DB AG; see **Table 6**	2.00	MJ/kWh	:= grid electricity	
Rock/soil excavation	0.03	MJ/kg	[7]	diesel for mining. w/o far-dist. transport	2.26	g/kg	[7]. [3]	diesel for mining. w/o far-dist. transport	1.0008	t/t	:=1 plus diesel consumpt.f. mining [7]	1.6
Sand	0.09	MJ/kg	[3]		12	g/kg	[3]	Mining sand in Germany	1.18	t/t	gravel/sand	
Sand+grit	0.03	MJ/kg	[9]		9	g/kg	[3]	:=50% pit gravel. beach gravel + 50% sand	1.18	t/t	sand/grit; w/o.electr.	
Steel	24.5	MJ/kg	[3]	steel. cold milled	1864	g/kg	[3]	steel. cold milled	7.52	t/t	83% oxygen-.17% electro-furnace	7.9
Steel/iron	21.0	MJ/kg	[3]. [6]	:=70% steel + 30% iron	1582	g/kg	[3]	:=70% steel + 30% iron	7.52	t/t	:= steel	
Thermal energy	2.12	MJ/kWh	[3]	district heat	445	g/kWh	[3]	district heat. w/o bonuses	0.168	MJ/kWh	heating	
Wood	13.6	MJ/kg	[6]	trimmed timber. from factory	98	g/kg	[6]	trimmed timber. from factory	6.50	t/t	pine. trimmed. dry	0.53

Remarks c.f.: calculated from (e.g. mix) w/o: without
distr.: distribution w/: with
assum.: own calculation/assumption

Table 3: Selected direct material and end energy consumption by main process element (MPE)

MPE	Module	Inventory data	Life cycle phase / working life	Data source / quality	per 100 person kilometres
Driving	traction energy	rail electricity: 22.5 kWh/tdkm (ICE)	use phase	measurements, literature, simulations	7.31 $kWh_{rail-el}$/100 pkm
	train board energy	rail electricity: 1.35 kWh/ tdkm (ICE)	use phase	measurements	0.437 $kWh_{rail-el}$/100 pkm
	Overhead energy, making up a train	rail electricity: 1.20 kWh/ tdkm (ICE)	use phase	literature	0.390 $kWh_{rail-el}$/100 pkm
	passenger transport to/from train station	petrol: 0.945 litres/passenger	use phase	modelled	420 g_{petrol}/100 pkm
Railway track	rail	steel: 282 t/rtkm	30 years(use)	literature, reliable	61.1 g_{steel}/100 pkm
	rail driveway (gravel bed)	concrete: 990 t/rtkm steel: 39.0 t/rtkm gravel: 7950 t/rtkm	30 years(use) 30 years(use) 15 years(use)	literature, reliable	210 $g_{concrete}$/100 pkm 8.5 g_{steel}/100 pkm 3400 g_{gravel}/100 pkm
	Points	heating (rail el.): 400 kWh/(points·a)	use phase	manufacturer supplied data	0.039 $kWh_{rail-el}$/100 pkm
	tunnels, mined	excavation soil: 270000 t/tukm concrete: 44000 t/tukm steel: 2100 t/tukm	100 years(use) 100 years(use) 100 years(use)	technical sketches	4000 g_{soil}/100 pkm 640 $g_{concrete}$/100 pkm 31 g_{steel}/100 pkm
	tunnels, trenched	excavation soil: 700000 t/tukm concrete: 71000 t/tukm steel: 2800 t/tukm	100 years(use) 100 years(use) 100 years(use)	technical sketches	6800 g_{soil}/100 pkm 690 $g_{concrete}$/100 pkm 27 g_{steel}/100 pkm
	glen bridges	concrete: 55000 t/brkm steel: 3000 t/brkm	100 years(use) 100 years(use)	technical sketches	270 $g_{concrete}$/100 pkm 15 g_{steel}/100 pkm
	road/railway bridges	concrete: 89000 t/brkm steel: 4900 t/brkm	50 years(use) 50 years(use)	based on costs + glen bridge data	190 $g_{concrete}$/100 pkm 10 g_{steel}/100 pkm
Railway passenger stations	operation	electricity: 9.72 Wh/passenger heating: 35.3 Wh/passenger drinking water: 196 g/passenger	use phase use phase use phase	annual costs	0.006 $kWh_{grid-el}$/100 pkm 0.022 kWh_{therm}/100 pkm 121 $g_{drinkingwater}$/100 pkm
	construction of buildings	concrete: 6 g/passenger bricks: 12 g/passenger	100 years(use) 100 years(use)	building volume data and BUWAL factors [15]	3.7 $g_{concrete}$/100 pkm 7.4 g_{bricks}/100 pkm
	maintenance of buildings	concrete: 70 mg/passenger bricks: 160 mg/passenger	use phase use phase	Construction data and maintenance costs	0.043 $g_{concrete}$/100 pkm 0.099 g_{bricks}/100 pkm
Train maintenance sites	operation	electricity: 0.132 kWh/tdkm heating: 0.588 kWh/ tdkm drinking water 3600 g/ tdkm	use phase use phase use phase	site balances	0.081 kWh_{-el}/100 pkm 0.36 kWh_{therm}/100 pkm 2215 $g_{drinkingwater}$/100 pkm
Train retrofitting factories	operation	electricity: 0.059 kWh/tdkm heating: 0.223 kWh/ tdkm drinking water: 281 g/ tdkm	use phase use phase use phase	site balances	0.0363 kWh_{net-el}/100 pkm 0.137 kWh_{therm}/100 pkm 173 $g_{drinkingwater}$/100 pkm
Szenario:	ballastless slab				
Railway track	rail driveway (ballastless) (instead of gravel bed)	concrete: 4500 t/rtkm steel: 132 t/rtkm	60 years(use)	manufacturer Rheda/Zueblin	490 $g_{concrete}$/100 pkm 14.3 g_{steel}/100 pkm

rtkm = rail track kilometres (two-way)
tukm = tunnel kilometres (kilometres of tunnel pipe, assuming two-way track per pipe)
brkm = bridge kilometres
tdkm = train drive kilometre

In the present study, the ballastless track system Rheda/Zueblin was investigated. Here, the railroad sleepers are jolted into a layer of concrete before allowing the cement to set. The elements of the traditional gravel bed track have a serviceable working life of between 15 and 30 years under high speed conditions. The life expectancy of the Rheda/Züblin track is stated to be 60 years.

Points are needed in order to move from one rail track to another. For the reference route, 2.1 points per average two-way rail track kilometre (rtkm) were counted, which can be assumed to be representative for high-speed railway routes in Germany[4]. The points have to be lubricated regularly and heated in winter to avoid icing.

[4] In France and Japan, for example, there are far fewer sets of points per kilometer.

Tunnels and bridges require a high material input for construction, primarily in the form of concrete (sand and cement) and steel for reinforcement. Considerable quantities of soil and rocks have to be excavated and moved. In Germany, railway tunnels dedicated for electrically driven trains are not illuminated and no air ventilation is required as is necessary for road traffic tunnels.

Further components of rail track infrastructure are the catenary system, signalling infrastructure, train overtaking stations, sound insulating walls and electric transformer stations for transforming the electricity of 110 kV to the 15 kV fed into the catenary. It could be shown that these components do not contribute significantly to the life cycle resource consumption of the ICE transport system, therefore their inventory data is not listed in Table 3.

Inventory analysis gives masses and energies per year needed to build and run a certain investigated section of rail track. They are allocated to train kilometres by dividing by the number of trains (including cargo trains) using this particular rail track section within a year. Trains making use of only a fraction of the reference route are counted with their respective relative travel-kilometres. For the reference route, which is one of the central north-south connections in Germany, the allocation factor corresponds to an average of 137 'virtual trains' per day using the whole 325 km of the reference route, that is one train every 10 minutes in both directions. Different methods of allocation (e.g. by ton kilometres and/or by considering increased dynamic loads caused by high-speed travel) might lead to different results. One should, therefore, clearly state how this allocation is performed in all studies investigating the impact of the transport infrastructure on life cycle aspects. For the circumstances of the reference route, a sensitivity analysis was done by alternatively allocating the track infrastructure on a ton-kilometre basis. In this case, this resulted in an allocation factor for the ICE transport system which was slightly 'better' (i.e. smaller) in comparison to the train kilometre allocation model used.

Apart from the rail track there are other MPEs contributing to the infrastructure of the ICE transport process, namely the *passenger train stations*, *train maintenance sites*, *train retrofitting factories and the energy distribution systems* (which distribute the 110kV electric energy from the power plant to the transformer stations of the rail track). In a broader sense, *vehicle manufacturing* can also be regarded as part of the infrastructure of the transport process chain.

For *passenger train stations*, the construction materials for the buildings and the electricity, heating energy and water consumption were evaluated and allocated to the reference unit of this MPE, the number of passengers boarding or disembarking. Activities not directly related to passenger transport in a railway station, such as the different shops and restaurants, which cater for passengers and visitors as well, and their relative share in the building and electricity, heating and water consumption, have not been included. Table 3 gives the inventory data referred to passengers and to 100 ICE person kilometre (pkm), which is the functional unit of the overall transport process relying on the services of the railway station.

For *train maintenance sites* and *train retrofitting factories*, site balances were available which quantify the water, electricity, heating energy, etc. consumed and the solid waste, waste water, secondary raw materials produced. This data has been allocated to the number of trains serviced per year and their average travelling distance between visits.

Fig. 2 sums up the reference units and the models used to allocate the inventory data of selective MPEs to the functional unit of the ICE transport process (100 pkm).

In total, the inventory analysis of the ICE transport on the reference route shows that the direct or end materials attributable to a 100-kilometre journey of a passenger add up to 12 kg, with gravel for track bedding (3.8 kg), drinking water for train toilets, train washing and on-board food services (2.3 kg), concrete for tunnels and bridges (1.8 kg) and steel (0.1 kg) being the main contributors.

3 Primary Energy and Resource Consumption: CED and MIPS

The life cycle primary energy demands were obtained by multiplying the inventory data by its respective CED-factors (see Table 1). Accordingly, the masses of the solid raw material resources that are 'used or touched' within the life cycle are calculated by applying the MIPS factors (without water and air). They can be visualised as filling a knapsack which a passenger 'has to carry' when travelling 100 kilometres by ICE.

From **Fig. 3** it can be seen that 47.9 kg of raw material are needed for every 100 ICE person kilometre on the reference route. 27 kg of this quantity are caused by the railway infrastructure, the rest by consumption of energy resources. Statistically, each German travels 145 kilometres per year by ICE. Taking the data from the present study, consumption of 70 kg of raw materials somewhere in the environment is associated with this use of the ICE. According to [11], an average total mass flow of 36 tons is needed to support all of these activities in a year. So, ICE transport currently has a stake of approx. 2‰ of the mass flows caused by the average German citizen.

In terms of primary energy requirements, expressed as petrol equivalents, the infrastructure contributes 0.5 litres, the overhead and board energies 0.8 litres and the traction process 2.4 litres of petrol equivalents to the 3.7 litres per 100 pkm total.

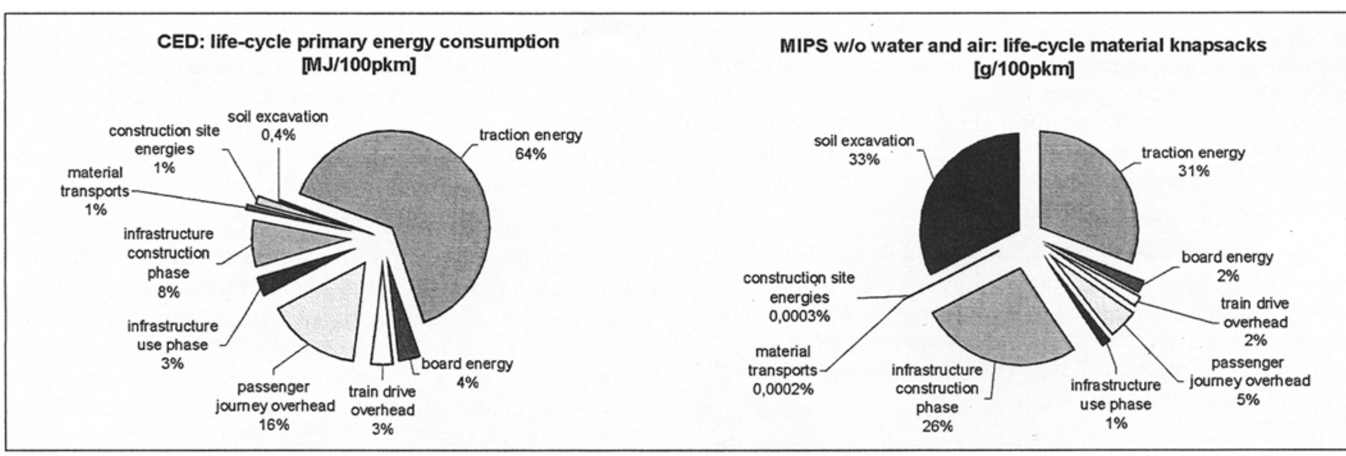

Fig. 3: CED, MIPS without water, air per 100 person kilometre

Obviously, travel-related activities contribute the major portion of the primary energy consumption of the ICE transport life cycle, whereas infrastructure accounts for only 13% of CED.

The CO_2 emissions per 100 ICE pkm are calculated as being 6.94 kg. This quantity is dominated by the energy consumption processes.

The end energy and material consumption, as well as their associated CED, MIPS (without water and air) and CO_2 emission values per 100 person kilometres ICE transport, are summarised in **Table 4**. These values can be used as input for other LCA studies where passenger transport by ICE has to be considered.

The Infras report [1] is one of the most complete LCA studies of a rail transport system available so far. In it, the following components of the ICE system are evaluated:

- operational phase of ICE2 (traction energy)
- construction, maintenance and disposal of ICE2 trains
- construction, maintenance and disposal of railway track infrastructure
- construction and use phase of rail tunnels

Infras quantified the infrastructure share of the whole life cycle primary energy consumption of the ICE person kilometre at more than 50%. This major difference to the 13% estimated in the present study stems partly from the top down approach employed by Infras. In the Infras study, the railway infrastructure of the whole country is distributed equally per train kilometre among all railway transport systems. This approach results in an average national value that does not, for example, take account of the differences in technology and train frequency between a high speed and a commuter railway track. In this way, Infras is using different models for allocating the yearly expenditures of the infrastructure to the person kilometre. This model is probably more appropriate for modelling 'average traffic' processes in LCA modules while the ecology profiles approach should be preferred when comparing specific traffic systems.

Regarding tunnels, Infras applies two different infrastructure models. The one which is used for the ICE[5] does not include ventilation, while the other one (modelling the other Swiss rail systems) assumes ventilation. When comparing the tunnel data given by Infras for non-ICEs to the ecology-profile results, the high electricity consumption attributed to the ventilation of the railway tunnels in Switzerland, necessary 'for thermal reasons', are another obvious difference. In Germany, the tunnels used by the ICE are not machine ventilated according to DB AG experts. Furthermore, the high amount of electricity attributed to operating the rail track and 'adjacent buildings' in the Infras study could not be confirmed for the high speed, state of the art reference route evaluated in Germany.

[5] The data for the Infras ICE process based on Frischknecht: Ökoinventare für Energiesysteme, Zurich, 1994.

Table 4: Consumption of end energies, direct/end materials, CED and MIPS as well as waste production and CO_2 emission for the ICE transport system according to the nature of the materials

	Direct masses / end energies	CED	MIPS w/o water and air	CO_2 emissions
		Input		
	[kWh / 100 pkm (ICE)]	[MJ / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]
Rail electricity	8.18	83.8	16.4	4.87
Grid electricity	0.124	1.33	0.248	0.0799
Thermal energy	0.521	1.10	0.100	0.257
	[kg / 100 pkm (ICE)]	[MJ / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]
Drinking water	2.51	0	0	0
	[kg / 100 pkm (ICE)]	[MJ / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]
Petrol (passenger overhead)	0.422	18.4	2.46	0.766
Gravel (ballast)	3.76	0.902	5.53	0.0639
Concrete	2.11	2.10	2.94	0.362
Sand/grit	0.812	0.0760	0.959	0.00950
Glass	0.00110	0.0157	0.00420	0.00127
Insulation material (mineral wool)	0.000677	0.00861	0.00385	0.000660
Plastics	0.00755	0.269	0.0658	0.0177
Soil/rock excavation	15.5	0.415	15.5	0.0350
Steel	0.210	5.14	1.58	0.390
Iron	0.0113	0.190	0.0794	0.0140
Aluminum	0.00597	0.855	0.404	0.0537
Copper	0.00627	0.293	1.57	0.0237
Non-ferrous metals (unspec.)	0.00106	0.0266	0.0316	0.00183
		[MJ / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]
primary energy for construction		2.41	0.000214	0.000203
		Output		
	[kg / 100 pkm (ICE)]	[MJ / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]	[kg / 100 pkm (ICE)]
waste water	2.27	0	0	0
waste/secondary raw materials	0.0928	0	0	0
Σ		**117 MJ / 100 pkm**	**47.9 kg / 100 pkm**	**6.94 kg / 100 pkm**

4 Representativeness: What about other Tracks and other Rail Transport Systems?

The ecology profile study describes the situation of the passenger ICE railway transport on the major high speed routes in Germany. In **Table 5**, the influence of major parameters on the lifecycle CED and MIPS values has been evaluated. For this, the reference route specific parameter values have been compared with the average data of the German railway grid. Each parameter has been changed one at a time, thereby keeping the other parameters constant, except for traction energy and passengers per train, which are interrelated depending on the type of the train in question. From the sensitivity data of Table 5 it becomes apparent that train capacity utilisation (passengers per train), traction energy (consumption, diesel or electricity drive), train load (e.g. trains per day) on the track and the share of tunnels have a strong influence on the ecological impact of the transport system. At least these parameters should be adapted when estimating ecological life cycle values for railway transport systems other than the ICE.

5 Interpretation: Major Conclusions

For passenger rail transport on the high speed tracks in Germany, rail infrastructure does not contribute the high share to environmental impact expected from other studies. Infrastructure under the conditions found in Germany provides only less than 15% of the total CED per 100 pkm. Traction energy consumption clearly dominates the primary energy of the life cycle. Therefore, the rail electricity mix and more efficient traction concepts are the most promising considerations for optimising the energy balance of the ICE transport (compare the CED factors of different mixes in **Table 6**).

Generally, when dealing with studies on passenger transport systems, close attention should be paid to the allocation of the infrastructure components between the different transport systems using them and to the amount of capacity utilisation which was assumed.

For most rail infrastructure components, the construction phase dominates the life cycle of these components. For example, for the rail tracks as a whole, the CED and MIPS of the construction phase are 15 times larger than those of the use phase. For railway stations, on the other hand, the CED of the media consumed in the use phase is twice as high as the CED of the station buildings construction phase.

Ballastless slab tracks, specifically the Rheda/Zueblin type evaluated, do not cause higher primary energy consumption on the 100 pkm level than the traditional gravel bed, provided that the assumption of 60 years life expectancy and a much reduced maintenance requirement are realistic. The MIPS requirements of the ballastless slab track are then considerably lower than for the gravel bed track.

Table 5: Sensitivity of the lifecycle impact of the rail passenger transport system

Parameters	Ecology profile	DB AG grid average	Concerns mainly	Influence on whole-lifecycle CED	Influence on whole-lifecycle water free MIPS
Passengers per train (capacity utilisation)	308 passengers/ICE (46% of ICE seats)	long distance: 206 passengers/train [a] commuter: 68 passengers/train [a]	per-100 pkm resource consumption for all MPE except railway stations	+ very high	+ high
Traction energy amount / type of traction	22.5 kWh/tdkm 15kV rail electricity (at pantograph)	32 kWh/tdkm [b]	traction energy for journey and train drive overhead		
Train load of track	137 trains/d (two-way track)	83 trains/d [c]	share and amount of per-100 pkm resource consumption for rail track and energy distribution	+ medium	+ high
Tunnels a) trenched tunnels b) mined tunnels	38% of rtkm 15% of rtkm 23% of rtkm	1.2% of rtkm 0.25% of rtkm 0.95% of rtkm	railway resource consumption	– small	– high
Bridges a) rail glen bridges b) railroad and roadway bridges	 8% of rtkm 1% of rtkm		railway resource consumption	– small	– small
Allocation by train or load km	by tdkm	–	share and amount of per-100 pkm resource consumption for railway and energy supply	– small	– medium
Number of points per rtkm	2.1 points/rtkm	2.6 points+crossways /rtkm [c]	energy demand for operation and maintenance of rail tracks	+ small	+ very small
Average travelling distance per passenger	325 km	ICE: 325 km long distance:250 km [a] commuter: 24 km [a]	share and amount of per-100 pkm resource consumption for railway stations and passenger drive overheads	+ very small	+ very small

rtkm = rail track kilometres (two way)
tukm = tunnel kilometres (kilometres of tunnel bore, assuming two-way track per bore)
tdkm = train drive kilometre
[a] calculated from [12]; [b] calculated from [13]; [c] calculated from [14]

+: ascends; –: decreases
very high: >50%; high: 50..20%;
medium: 20..5%;
small: 5..1%; very small: < 1%

Table 6: Energy mixes and resulting CED factors

References	DB AG rail 1999 DB AG	Grid Germany 1999 VDEW, ZfK, DB AG	Grid Norway Gemis 4 [3]	Grid Swiss Gemis 4 [3]	OECD mix 2000 IEA.org
Water power	9.0%	4.6%	99.50%	56.48%	19%
Wind power	0.4%	1.3%			
Photovoltaic power	0.4%	0.01%			
Pit coal combustion	24.3%	27.5%	0.20%		30%
Lignite combustion	22.5%	25.3%		1.55%	7%
Oil combustion	1.5%	1.0%		0.52%	9%
Gas combustion	13.7%	9.3%	0.30%	1.52%	19%
Nuclear power	28.2%	29.3%		39.93%	17%
Total generation	1.11E+10 kWh	4.23E+11 kWh			1.52E+13 kWh
CED factor [MJ/kWh]	**10.3**	**10.4**	**4.3**	**7.8**	**9.6**
Each w / rail-typical 10% distrib. losses[5] applied					

Tunnels and rail bridges cause high specific resource consumption. Apart from this, tunnels impose significant restrictions on train speed and increase the traction energy as well (aerodynamic effects). Therefore, when planning new track routes, it is important to make efforts in exploring alternative track routes from the viewpoint of life cycle aspects.

When regarding the use phase only, the heating of electric rail points was identified as one of the most relevant sources of energy consumption. German rail tunnels are neither lighted nor ventilated. However, if ventilation were necessary, as is the case for road tunnels, this would result in energy demands significantly higher than those for rail-points heating. In contrast, tunnel lighting would add only about 1/3 of the electricity amount used for rail-points heating.

6 Outlook

It is tempting to compare the results on the ICE to highway road traffic. A first estimation showed that ICE passenger transport has little to fear in such a comparison to current-state car technology, especially at the per-100-kilometres level. However, as little in-depth data is available on the infrastructure for road traffic and as comparative studies should be critically reviewed by the stakeholders [16], no quantitative statements shall be presented here.

Three major directions for further investigation on passenger transport systems appear most desirable. Firstly, the results on the ICE should be compared with data on the French and Japanese high speed passenger trains. Secondly, the scope of data application could be improved by investigating the differences to other rail based passenger transport systems. Thirdly, sound data and models for comparisons to highway road traffic and aviation are needed. In each case, further inventory data would have to be collected.

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References

[1] Maibach M, Peter D, Seiler B (1995): Ökoinventar Transporte – Grundlagen für den ökologischen Vergleich von Transportsystemen und den Einbezug von Transportsystemen in Ökobilanzen. INFRAS, Zurich 1995; updated 1999

[2] VDI Association of Engineers Germany (1997): Cumulative energy demand – Terms, definitions, methods of calculation. Beuth, Berlin/Vienna/Zurich

[3] Institute for Applied Ecology, Öko-Institut (2001): Global Emission Model for Integrated Systems – GEMIS 4.0. http://www.oeko.de/service/gemis/english/index.htm; status: 05/2001

[4] MIPS online (2001): http://www2.wupperinst.org/Projekte/mipsonline/; status: 07/2001

[5] Deutsche Bahn AG (2000): Systemgrenzen Umrechnungsfaktoren für Energiekennzahlen. DB AG internal paper

[6] Forschungsstelle für Energiewirtschaft FfE (2001): Analyse von Energie- und Stoffströmen – Basisdaten für die ökologische Bewertung von Unternehmen, Wirtschaftsgütern und Dienstleistungen. http://www.ffe.de/details/gabie/bilanz.htm; status 2001

[7] Eyerer P, Reinhardt HW (2000): Ökologische Bilanzierung von Baustoffen und Gebäuden – Wege zu einer ganzheitlichen Bilanzierung. Birkhäuser

[8] Institute for Applied Ecology, Öko-Institut (2001): Kumulierter Energie-Aufwand: mehr als eine Zahl; http://www.oeko.de/service/kea/; status: 2001

[9] Hübner H, Dunkel T et al. (1997): Transrapid zwischen Ökonomie und Ökologie – Eine Technikwirkungsanalyse alternativer Hochgeschwindigkeits-Verkehrssysteme. DMV

[10] Gawel E (1998): Das Elend der Stoffstromökonomie – Eine Kritik. Konjunkturpolitik 44

[11] Schütz H, Bringezu S (1993): Major Material Flows in Germany. Fresenius Environmental Bull 2, 1993, 443–448

[12] Deutsche Bahn AG (2000): Geschäftsbericht 2000 Teil 2: Daten und Fakten. http://www.bahn.de/extrahtml/pdf/daten_und_fakten_2000.pdf

[13] Ilgmann G (1998): Der Zukunft verpflichtet – Gewinner und Verlierer einer CO_2-Steuer im Güter- und Personenverkehr. Ludwig Bölkow Stiftung, Ottobrunn

[14] Deutsche Bahn AG (2000): Daten/Fakten DB Netz 2000. http://www.bahn.de/konzern/netz/wir/die_bahn_ziele_fakten.shtml; status: 10/2001

[15] Bundesamt für Umwelt, Wald und Landschaft (1995): Bauprodukte und Zusatzstoffe in der Schweiz. Schriftenreihe Umwelt 245, BUWAL; Bern

[16] ISO TC 207/SC 5 (1998): ISO 14040: Environmental management – Life cycle assessment – Principles and framework. Beuth

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